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ABSTRACT

"Machine controlled adaptive training is a promising concept. In adaptive training the task presented to the trainee varies as a function of how well he performs. In machine controlled training, adaptive logic performs a function analogous to that performed by a skilled operator." This study looks at the ways in which gain-effective time constant product, system compensation, and forcing function amplitude compare as adaptive variables, in terms of trainee performance, and at the differences in trainee performance between machine controlled and manual adaptation for the above variables. Eight independent groups, including one control group, were tested under different methods of training. Principal results show that manual adaptation is slightly superior to automatic adaptation, although this could be a function of the difference in performance measurement levels. Gain-effective time constant product is slightly superior to forcing function amplitude as an adaptive variable. System compensation, as implemented for this experiment, is not a satisfactory adaptive variable. Nor are aiding and quickening. (JK)

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ADAPTIVE TRAINING OF MANUAL CONTROL:

1. COMPARISON OF THREE ADAPTIVE VARIABLES AND TWO LOGIC SCHEMES

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ADAPTIVE TRAINING OF MANUAL CONTROL: I. COMPARISON OF THREE ADAPTIVE VARIABLES AND TWO LOGIC SCHEMES

ABSTRACT

Gain-Effective Time Constant product (KT), System Compensation (SC) (a condensation of aiding and quickening) and Forcing Function (FF) were compared as adaptive variables in an adaptive training experiment using 104 subjects. Comparison was also made of Automatic and Manual adjustment of the difficulty level determined by the level of the adaptive variables during training. Results showed KT to be slightly superior to FF as an adaptive variable while SC produced poor performance and a high rate of failure. Study of the results suggests that principles underlying KT and a correct form of SC can be used to develop an optimal method of shaping operator behavior. It was concluded that conventional concepts of aiding and quickening cannot be implemented as satisfactory adaptive variables. The results were additionally interpreted to indicate that logic for adjustment of difficulty level should utilize a performance measurement interval longer than 5 seconds.

FOREWORD

This document reports the results of an 18 month investigation of adaptive training in manual control of a single-axis tracking task. This effort was initiated in March 1969.

Three different adaptive variables (gain-effective time constant product, system compensation, and forcing function), and two different adaptive logics (manual and automatic) were compared during the acquisition and transfer of a single-axis compensatory manual tracking task. The results should provide useful guidelines for the design and implementation of adaptive training techniques.

These comparisons should be extended to multi-axis control tasks, and should be expanded to include an investigation of the problems of performance measurement, especially performance measurement intervals, in adaptive training of manual control tasks.

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Arrangements for subjects to participate in the experiment were made by Drs. David Abbott and Phillip Tell of the Florida Technological University Psychology Department.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

One of the most promising concepts to emerge from recent research in training technology is that of machine controlled adaptive training (Kelley, 1962). In adaptive training the task presented to the trainee varies as a function of how well he performs. In machine controlled training, adaptive logic performs a function analogous to that performed by a skilled instructor.

The utility of the machine controlled adaptive training concept has been demonstrated for flight training by Lowes, Ellis, Norman and Matheny (1968) and it is currently being implemented in the 2B24 synthetic flight training system for helicopters. However, several problems remain to be solved before the concept can be utilized to its fullest potential.

As Regan (1969) has pointed out, among the problems awaiting solution is the choice of the adaptive variables, i.e., along what continuum should difficulty be varied as trainee skill increases in the adaptive training situation? In particular, in learning to control the spatial movement of a vehicle what dimensions are most suitable for variation to produce change in task difficulty? Several have been proposed but few have been empirically tested. Only two major studies of adaptive training in a flight training context have been conducted and both of these have used the same adaptive variable - turbulence amplitude (Wood, 1969; Lowes et al., 1968).

Among the dimensions of task difficulty which have been proposed for variation in adaptive training are:

- Changes in control order (Hudson, 1964)
- Changes in amount of display quickening, (Birmingham, Chernikoff & Ziegler, 1962)
- Changes in the amount of aiding, (Kelley & Wargo, 1968)
- Changes in forcing function level, (Kelley, 1962)
- Changes in the effective time constant of vehicle response (Matheny, 1969; Matheny & Norman, 1968).

The study reported here effects a comparison of the suitability as adaptive variables of the Effective Time Constant, Forcing Function Amplitude (turbulence) and System Compensation (a condensation of aiding and quickening). In addition, machine controlled training is compared with more conventional, manually controlled training. Definition of the adaptive variables and

rationale for variable selection and the method of testing is presented in the following sections.

SECTION II

STATEMENT OF THE PROBLEM

Basically, two questions are to be answered by this study:

- In terms of trainee performance, how do Gain-Effective Time Constant product, System Compensation and Forcing Function Amplitude compare as adaptive variables?

- What are the differences in trainee performance between machine controlled and manual adaptation of the above variables?

A more detailed formulation of these questions together with subsidiary questions is the subject of following sections.

1. PRIMARY QUESTIONS

Perhaps the most useful approach to answering the two broad, basic questions is to examine initial and transfer task phases of training in terms of time to reach a criterion level of performance. From this standpoint the basic questions may be cast more explicitly as follows:

For both first task and transfer task training, what are the relative requirements in terms of trials to reach criterion for;

- Automatic, machine controlled adaptation of task difficulty?

- Manually controlled adaptation of task difficulty?

- Fixed (non-adaptive) task difficulty?

- Gain-Effective Time Constant product as an adaptive variable?

- System Compensation as an adaptive variable?

- Forcing Function Amplitude as an adaptive variable?

2. SUBSIDIARY QUESTIONS

Because a given performance criterion can possibly be satisifed with a variety of methods of control manipulation, control technique under each condition of training should be studied. Thus, an additional question is:

- How is control tecnnique affected by method of training?

A second question relates the similarity of the training and transfer tasks. For assessing the perceptual fidelity of simulation, Newell (1962) has proposed standards derived from ratings of a number of systems by expert pilots. Matheny and Norman (1968) have suggested the gain-effective time constant product. The question is:

- For a training task and a transfer task for which the expected pilot ratings differ but the gain-effective time constant product is the same, which is more predictive of transfer task performance, the ratings or the product?

SECTION III

METHOD

1. OVERVIEW

The experimental design employed was the transfer of training paradigm described as Design III by Murdock (1957). In this design, training time to reach criterion on the transfer task under an experimental training method is compared to time to criterion required by a control group receiving training on the transfer task only. Positive transfer is said to occur when an experimental training group reaches criterion on the transfer task in fewer trials than are required by the control group.

Eight independent groups of eight subjects each were tested under different methods of training. One of the groups was a control group while seven groups were trained experimentally. Two tasks were used: a training task and a transfer task. All experimental groups were trained, each by a different method, to the same level of proficiency on the same training task before being tested on the transfer task.

The control group practiced exclusively on the final, transfer condition until it was mastered. One experimental group practiced first on the criterion level of difficulty of the training task, until it was mastered, then transferred to the transfer condition on which they practiced until it was mastered. Mastery of a condition was defined as performing two trials in succession within a specified error tolerance.

The remaining six experimental groups were divided into automatically and manually adapted groups for each of the three adaptive variables. The manually adapted groups practiced, until mastered, each of 3 successive, progressive difficulty levels of their respective adaptive variables; they then practiced the criterion level of the training task until mastered and finally transferred to the transfer task to practice it until mastered. Mastery of one of the first 3 levels of the adaptive variable was defined as one trial[1] within error tolerance while mastery of the criterion level and transfer tasks was two trials in succession within tolerance, as for the control group.

For the automatically adapted groups, the levels of the adaptive variables were continuously changing, based upon trainee performance, during each trial. Difficulty automatically progressed and, if necessary, regressed, ranging to either higher or

[1] Only one trial, rather than two, was used as the basis for advancement in early training so that the minimum possible training time would not be unduly large and create an experimental artifact with respect to the training time required by different conditions.

lower levels than that representing the criterion level. The automatically adapted task was said to be mastered when the average difficulty level during a trial equaled or exceeded the criterion level for two trials in succession. After mastering the automatically adapted task, these groups transferred to the transfer task under the same conditions as the other groups.

While the data to be collected of most interest were the number of trials required by the different groups to master the original training and the transfer tasks, control input measures, error scores, and difficulty level values during training were recorded.

Two tasks were used so that the differential effects of the adaptive variables and adaptive logic upon both original training and transfer of training could be assessed. The most important comparisons to be made were those based on transfer task performance, for only the transfer task situation can be used to determine the extent to which the trainee can make use of what he learned in training. That is, performance on the first task is indicative of progress in training but transfer task performance is a measure of what subjects have been trained to do.

The experimental design is summarized in Table I. Details of the experiment are presented in following sections.

2. RATIONALE FOR SELECTION OF TASK AND ADAPTIVE VARIABLES

The trainee's basic task was an analog of maintaining an aircraft in a level pitch attitude using a heads-up type display while penetrating turbulent air representative of cumulus clouds. This single dimension task is one which can be learned in a reasonable period of time and also is one which satisfies the following ground rules.

- o The task required of the trainee must be a reasonable analog of a real world training task.
- o The task configuration must be simple enough to permit ready analytical manipulation.

In the context of this task it was possible to select adaptive variables which:

- o Could be stated in language which has meaning for those charged with responsibility for implementing training concepts into training hardware.
- o Could be stated explicitly and quantified so as to establish empirical relationships between their variation and trainee performance.

TABLE 1. SUMMARY OF EXPERIMENTAL DESIGN

GROUP	TRAINING	TRANSFER CRITERION	TRANSFER
XF	None	None	Transfer Task
CR	Criterion Level of Training Task	1° or Less Error on Two Successive Trials	Same as Above
MSC	Progression Through Three Levels of System Compensation to Criterion Level of Training Task	Same as Above	Same as Above
MKT	Progression Through Three Levels of Gain-Effective Time Constant Product to Criterion Level of Training Task	Same as Above	Same as Above
MFF	Progression Through Three Levels of Forcing Function Amplitude to Criterion Level of Training Task	Same as Above	Same as Above
ASC	Automatic Progression and Regression of Level of System Compensation	100% or Greater Difficulty on Two Successive Trials	Same as Above
AKT	Automatic Progression and Regression of Level of Gain-Effective Time Constant	Same as Above	Same as Above
AFF	Automatic Progression and Regression of Level of Forcing Function Amplitude	Same as Above	Same as Above

2.1 AIRCRAFT SIMULATION. To keep the simulation reasonably simple, the aircraft dynamics were restricted to the short period approximation of the pitch angle response. So that previously developed data could be used in implementing the Gain-Effective Time Constant product condition, the form of the transfer function for the training task was the same as that used by Matheny and Norman (1968).

While this transfer function is unusual in that it does not have a short period lead term, data reported by Jex and Cromwell (1962) were interpreted to indicate that this is not a serious drawback. Their data for a comparatively narrow range of values indicate a steady improvement in pilot rating with decreasing short period lead. It was assumed by extrapolation that a simulation with no short period lead, while somewhat unrealistic, was justified since it would probably be rated highly by experienced pilots.

For the transfer task, a short period lead was added, but only so that an aircraft with the same Gain-Effective Time Constant product but with a different, lower pilot rating would result. As a consequence, another unusual transfer function was produced with the lead occurring at a higher frequency than the short period -- the reverse is typical. As mentioned in Section II, the intention was to compare the gain-effective constant product with pilot ratings, as used by Newell (1962), as a basis for judging the perceptual fidelity of simulation.

Newell has argued that, for expert pilots, changes in pilot ratings with changes in aircraft characteristics indicate changes in pilot technique required to maintain constant performance, with lower ratings indicating that more difficult techniques are required. For novice pilots with less ability to change technique, aircraft configurations with low expert rating should produce inferior novice performance.

Data reported by Kolk (1961) indicate that if any effects of short period lead variation on pilot opinion are ignored, a short period natural frequency of 2.5 radians/sec would be rated GOOD while one of 1.0 radian/sec would be rated POOR, with the damping ratio 0.7 in both instances. These values correspond to the training and transfer tasks, respectively. Except for differences due to method of training, one would expect no differences in the ability of subjects to perform the training and transfer tasks based on the equivalent gain-effective time constant products. Yet the lower pilot rating suggests that performance on the transfer task should be inferior to that on the training task.

2.2 FORCING FUNCTION AMPLITUDE. The degree of turbulence imposed upon a system being controlled is a quantifiable dimension which is related to task difficulty and is present in a real world system. Increasing the level of turbulence imposed upon a system makes the control task increasingly more difficult for the trainee.

Therefore, it lends itself to use as an adaptive variable in the adaptive training situation and has been investigated in this regard by Wood (1969) and Lowes et al. (1968). What appears to be a disadvantage to its use as an adaptive variable is that in systems which are fundamentally difficult to control because of their system dynamics, level of difficulty cannot be decreased below the level set by the system. Thus, in the initial stages of training the use of turbulence as an adaptive variable may not be as appropriate as the use of some other.[1] It has been included in this study primarily as a reference condition to permit comparison with earlier work.

2.3 SYSTEM COMPENSATION. Two other candidate adaptive variables are amount of quickening and amount of aiding. Aiding appears to be most useful in performing a positioning task in which a constant rate of change of position is the required output and when the forcing function is relatively low in frequency (Morgan, Cook, Chapanis & Lund, 1963). The efficacy of aiding, however, has been seriously questioned even in this application (Simon & Smith, 1956). Further, a characteristic of aiding is that the operator must make more control movements to obtain a simple machine output than he would in unaided tracking (Morgan et al., 1963).

With quickening, on the other hand, the operator's display shows what he should do with his control. Moreover, quickening appears most useful when a system containing integrations, such as an aircraft or submarine, must be operated (Morgan et al., 1963). In fact, Sweeney, Bailey and Dowd (1957) showed that control of ground speed in a simulated hovering helicopter can be substantially improved through the use of quickening. In addition, Holland and Henson (1956) have demonstrated positive transfer from quickened to unquickened systems and vice-versa.

Thus, quickening appears highly suitable as an adaptive variable except that a hierarchy for the removal of quickened elements from the operator's display does not exist. In addition, special displays are usually required. That is, a quickened display does not show the actual state of the system so that additional displays are required to provide this information (McCormick, 1964). It should be noted further that in much of the research on quickening, little attention has been paid to this point and error scores have been derived not for the system output but for the displayed error (Birmingham, Chernikoff, & Ziegler, 1962; Holland & Henson, 1956; and Birmingham, Kahn & Taylor, 1954, for example).

Depending then upon whether error is measured at the system output or at the display, a given system configuration may be

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[1] The use of turbulence in conjunction with other adaptive variables, however, could prove to be an efficient means for varying task difficulty over a wide range.

considered to be either aided or quickened. The investigators cited above appear to have failed to make a proper distinction by using the term quickening to describe what was really an aided system. Further, only crude, qualitative statements have been made regarding the proportions in which the various movement elements should be combined to provide assistance in the control task.

For purposes of clarifying the apparent confusion the authors propose the following definitions.

- A man-machine system is said to be aided if the total output of the system is considered to consist of the output of the machine plus additional feed forward functions of the operator's output.

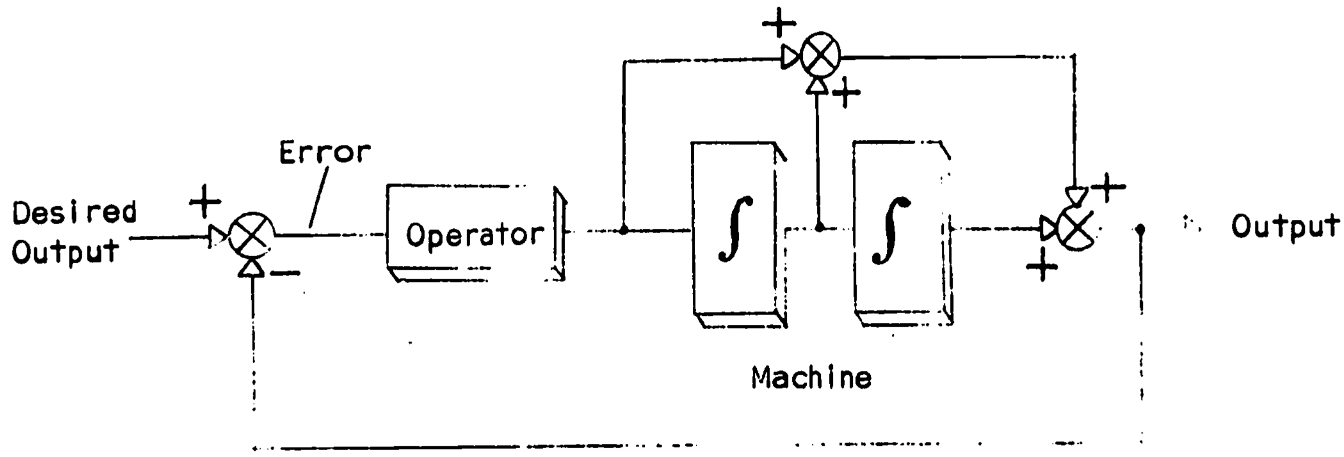
In this case the total output is fed directly into a device which yields as an output the difference (i.e., error) between the system input (in this case, the desired system output) and actual system output. (See Figure 1.) This error information is then supplied directly to the operator.

- A man-machine system display is said to be quickened if derivative functions of the machine output are fed back for comparison with the system input at the operator's display and the output of the system is considered to consist only of the machine output.

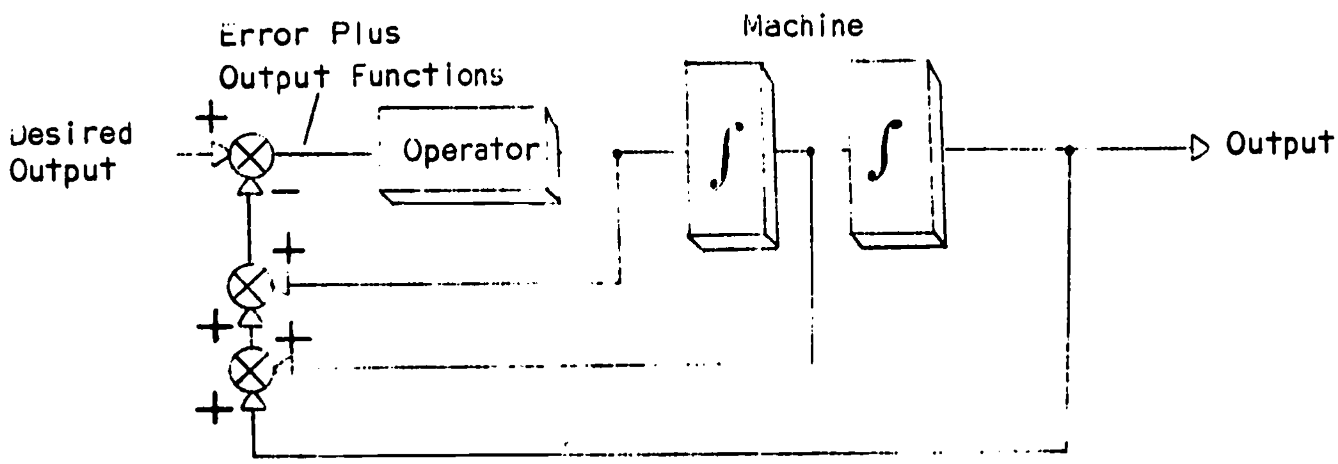
In this case system error, defined as system input minus system output, does not appear explicitly in the error display. (See Figure 1.) The operator receives only information concerning the difference between system input and some function of system output. In such a single display system, system error nulling is not possible.

Clearly the definition of an aided or quickened system depends upon the explicit definition of the system output. In a physical system there is no ambiguity as to what constitutes the true system output. In synthetic experimental devices, however, the definition is frequently arbitrary. In order to define the task in the present study as control of the short period pitch response of an aircraft, the experiment must be considered as a study of aiding. On the other hand, as a synthetic system the study may also be construed as quickening, in which true system error nulling is not a performance criterion.

The behavior of the operator's display appears to be the same for either aided or quickened systems - what seems to have formed the distinction for previous investigators is whether integrators have been added to aid a positioning system or position information has been added to quicken a system containing integrations. The result in either case is to



AIDING



QUICKENING

Figure 1. Illustration of Aiding and Quickening

compensate the system for the operator so that his task is simplified. Birmingham and Taylor (1954a, 1954b) have argued that system compensation in accord with their Design Philosophy for Man-Machine Control Systems is the underlying principle of both aiding and quickening, that principle being:

> "Design the man-machine system so that (1) the band-pass required of the man never exceeds three radians per second, and (2) the transfer function required of the man is, mathematically, always as simple as possible, and, wherever practicable, no more complex than that of a simple amplifier." (1954a, p. 7)

Their example application of the principle and, indeed, all examples of aiding or quickening in the previously cited references show the operator's display to contain, in addition to the machine output, a weighted sum of the inputs to each stage of integration in the machine. In each instance, the uncompensated system transfer function, in Laplace transform notation, is of the form:

$$O(s) = \frac{k}{s^n} I(s)$$

which means that the output O(s) is equal to the input I(s) multiplied by a gain constant, k, and integrated n times. For the compensated system (i.e., aided or quickened) the incorporation of the inputs to each stage of integration adds a lead of order n to the system transfer function:

$$O(s) = \frac{k}{s^n} \left(\frac{A}{k} s^n + \frac{B}{k} s^{n-1} + \ldots \quad 1\right) I(s)$$

where A, B, etc. are the weights for the various inputs fed forward to form the machine output. Evidently, this is the generic form for system compensation.

Real systems are rarely pure integrators; usually there are feedback loops which create lags of varying order. A lag will, however, behave as a pure integrator for input frequencies greater than the natural frequency of the lag. That is, for example, for input frequencies greater than 1/T:

$$\frac{k}{Ts + 1} \overset{\circ}{=} \frac{k}{s}$$

In a system such as a submarine where the control inputs are high in frequency in comparison to the natural frequencies of the system, it is reasonable to represent the system with pure integrations. In that case, for system compensation as an adaptive variable, all of the weights may be changed at the same rate as a function of difficulty level, the approach taken by Birmingham et al. (1962).

But, in aircraft pitch control, the input frequencies are in the same range as the short period natural frequency. Thus, the system cannot be assumed to behave as pure integrations. If the same form of compensation is used, a lead of order n, the coefficients (weights) cannot be changed at the same rate and achieve the desired variation in difficulty. In this case, the coefficients in the lead may be made such that the lead may be factored into two components, one of which cancels the effects of lags with the other operating on any pure integrations in the previous manner.

That is, for a system such as that used in the present study:

$$O(s) = \frac{k}{s\ (s^2/\omega^2 + 2\zeta\ s/\omega + 1)}\ I(s)$$

a third order lead may be added with coefficients such that it can be factored into first and second order leads:

$$O(s) = \frac{k}{s\ (s^2/\omega^2 + 2\zeta\ s/\omega + 1)}\ (Xs + 1)\ (Ys^2 + Zs + 1)\ I(s)$$

With $Y = 1/\omega^2$ and $Z = 2\zeta/\omega$ at the lowest levels of difficulty, the second order lag will be cancelled and changes in X will vary the amount of system compensation in the manner of Birmingham and Taylor (1954a, 1954b). After X reaches zero with increasing difficulty level, holding Z in the proper relationship to Y and decreasing the value of Y with further increases in difficulty will progressively "uncancel" the lag until the fully uncompensated aircraft response is reached. For increases in difficulty beyond criterion, "negative compensation" may be provided by re-introducing X with negative sign.

For a system such as that above, let A be the feed-forward weight for the input to the last integration, B the weight for the second integration, and C the weight for the control input. Further, let $Y = (Z/2\zeta)^2$. Then it can be shown that for Y greater than zero (difficulty less than criterion):

$$A = kZ$$

$$B = \frac{\omega}{k}\left(\frac{A}{2\zeta}\right)^2$$

$$C = kX$$

For difficulty greater than criterion, $A = kX$, $B = C = 0$.

Table 2 shows the variation of A, B and C as a function of difficulty used to accomplish the above scheme. The resulting overall effect in the experiment conducted during this study was analogous to reducing the extent of autopilot or Stability Augmentation System assistance to increase difficulty until the unassisted state was reached. Progressively more "negative assistance" was then introduced for levels beyond criterion.

TABLE 2. VARIATION OF COEFFICIENTS WITH DIFFICULTY LEVEL

	DIFFICULTY LEVEL			
	BELOW AN INTERMEDIATE POINT	BETWEEN INTERMEDIATE AND CRITERION	CRITERION	GREATER THAN CRITERION
X	INVERSELY PROPORTIONAL TO DIFFICULTY	ZERO	ZERO	PROPORTIONAL TO DIFFICULTY
Y	$\frac{1}{\omega^2}$	$[\frac{Z}{2\zeta}]^2$	ZERO	ZERO
Z	$\frac{2\zeta}{\omega}$	INVERSELY PROPORTIONAL TO DIFFICULTY	ZERO	ZERO
A	$\frac{2k\zeta}{\omega}$	kZ	ZERO	kX
B	$\frac{k}{\omega}$	$\frac{\omega}{k}[\frac{A}{2\zeta}]^2$	ZERO	ZERO
C	kX	ZERO	ZERO	ZERO

2.4 GAIN-EFFECTIVE TIME CONSTANT PRODUCT. As presented previously (Matheny, 1969; Matheny & Norman, 1968), the effective time constant (t_e) is a construct which embodies machine properties described by the equations of motion of the vehicle and the operator property of level of threshold of perception of vehicle output.[1] The construct has been presented as a basic measurable parameter of the man-machine combination which constitutes an independent variable predictive of task difficulty. It is proposed as a quantifiable construct based upon properties of man and machine and deterministically related to them. The qualities of its being based upon specific properties of the machine, functionally related to task difficulty and being specifiable in terms meaningful to the system design engineer argues for its potential as a realistic and useful way of adaptively varying the training task.

Experimentation (Matheny & Norman, 1968) has shown t_e to be related to final level of precision of control and to rate of learning. It was also found that level of performance is related

[1] It should be noted that the threshold here is not an absolute psychophysical threshold in the usual sense, but rather an effective threshold defined by operator reaction to system output - a threshold of indifference. It is arbitrarily assumed fixed at a reasonable, empirically determined, value.

to the interactive effect of t_e and steady-state system gain (k) as expressed by the product of the two (kt_e). The effect of gain is particularly evident during the early training trials with the effect decreasing as learning progresses. It was further found that the machine properties of gain (k), frequency (ω) and damping (ζ) are not, as individual parameters, strongly related to control behavior. Their proper combination into an effective time constant (t_e) for the system was shown to result in t_e being related to performance.

Matheny and Norman (1969) suggested that at the beginning of training a low value for both gain and t_e be provided. Based upon student improvement gain would then be increased to provide a more difficult task followed by increasing t_e to make the task progressively more difficult.

Aside from the above suggestion a rationale for this progression in gain and then t_e can be developed from an analysis of the closed-loop task. In such a task the trainee is required to learn to move his control such that he nulls an error between some index indicating the system performance and some standard or referent. Normally, some external forcing function is imposed upon the system which tends to introduce divergence between the controlled index and the referent. Also, the system which the operator is controlling is sometimes unstable or tends to drift or otherwise accumulate error between the two indices.

The movements which the operator must make in nulling the error are dictated by the properties of the system through which he is operating and the characteristics of the forcing function. If it is assumed that learning to control the closed-loop tracking task is dependent upon the trainee's observation of the system output as a result of his control inputs, then the trainee must learn the relationship between movements of his control which serve as inputs to the system and the resulting system output. Through exploratory movements of the controls and observations of the results of system outputs (feedback) he learns the appropriate control movements for controlling the system and nulling errors.

For commanding the system output to perform in a certain way, e.g., move the nose of the aircraft upward to a new position, the system requires that the controls be moved in a certain spatial and temporal pattern which the trainee must learn if he is to command the system correctly. For the most part, the temporal pattern of movement required is dictated by the system dynamics and the expected performance; the size or amount of movement is dictated by the steady state gain of the system. That aspect of the system dynamics primarily affecting the time scale of the required control movement is the "time constant" of the system, i.e., some systems follow the movements of the control very rapidly while others lag the control input.

The trainee's problem is one of learning a spatial and temporal pattern of movement appropriate to the system output which he wishes to command. In learning the spatial pattern of movement required, a high steady state gain will require a much smaller extent of movement than will a low gain. At some high level of gain, the system output will reflect not only the overall spatial pattern of control movement which the operator makes in order to command the system but will also reflect any random or erratic movements (noise) imposed on the control. It would appear, therefore, that the gain of the system must be low enough so that early in the training period the trainee can learn the gross pattern of control movement without the necessity for sorting out of the system output those random, erratic and irrelevant control movements which may be introduced into the control. Once the gross pattern of control movement is learned the gain may be raised progressively so that he controls the system output with finer manipulations of the control.

At the same time the trainee is learning the spatial pattern of movement the correct temporal pattern of movement is required. If the effective time constant of the system is such that the system output lags far behind the control input, feedback will be delayed and the student cannot associate the system output with the particular control input being made. Thus, shorter time constants are appropriate during the early stages of learning. This permits the student to get immediate feedback as to the results of his control input and to make adjustments such that his inputs become more and more appropriate to the system output which he wishes to command. Upon his mastery of the spatial pattern of control movement required the time constant of the system may be progressively lengthened so that he may learn the lead or anticipation required in control input in order to bring about the appropriate system output which he wishes to command.

Gain-Effective Time Constant product was implemented as an adaptive variable by setting t_e as short as practicable and gain at one quarter of the final value for the lowest level of difficulty. With increasing difficulty gain increased while the effective time constant remained short until gain was at the final value at an intermediate point representing approximately 60% of the criterion level. The effective time constant was then lengthened for further increases in difficulty, progressing beyond the value for the criterion level for levels of difficulty greater than criterion.

2.5 SUMMARY OF ADAPTIVE VARIABLE CHARACTERISTICS. At the criterion level of difficulty, the task presented to the trainee was identical for all three adaptive variables - differences arose as difficulty varied from criterion. For Gain-Effective Time Constant product and System Compensation conditions, turbulence remained constant at the criterion amplitude while aircraft response to controls varied with changes in difficulty

level. On the other hand, for the Forcing Function Amplitude condition, the aircraft response remained constant and the amplitude of the turbulence varied with difficulty level. Thus, Forcing Function Amplitude acted directly on the system error while Gain-Effective Time Constant product and System Compensation acted indirectly, through the trainee. Hence, for adaptive logic based on system error, and under the Forcing Function Amplitude condition difficulty level may have been to some extent independent of trainee action (this point will be developed further in Paragraph 3.1).

As difficulty level varied, the form of the transfer function for the aircraft remained constant under the Gain-Effective Time Constant product condition but changed under System Compensation. With the latter, the responses required of the trainee changed more in a qualitative sense than those required under the former condition.

Table 3 summarizes important aspects of each condition. The question mark under Column 3 for Forcing Function Amplitude reflects the possible effects of reduced display ambiguity. It can be argued that with less turbulence, aircraft response may be more readily distinguished from the turbulence, thus permitting faster display interpretation and hence quicker feedback. This is probably not the only dimension along which this variable accomplishes changes in difficulty

TABLE 3. COMPARISON OF ADAPTIVE VARIABLES

	CAN GET EASIER THAN BASIC SYSTEM	ACTS DIRECTLY ON SYSTEM ERROR	FASTER TRAINEE FEEDBACK AT LOW DIFFICULTY	CONSTANT FORM OF AIRCRAFT TRANSFER FUNCTION	BASIC DIMENSION OF CHANGE FROM CRITERION AT LOW DIFFICULTY
FORCING FUNCTION AMPLITUDE	No	Yes	?	Yes	Reduced Turbulence Amplitude
SYSTEM COMPENSATION	Yes	No	Yes	No	Complexity of Operator Behavior Reduced (Required transfer function simplified)
GAIN-EFFECTIVE TIME CONSTANT PRODUCT	Yes	No	Yes	Yes	Aircraft More Responsive but Less Sensitive

3. RATIONALE FOR ADAPTIVE LOGIC

Adaptive logic schemes - the means for changing difficulty level as a function of trainee performance - may be considered to differ basically in the extent to which they adjust the task to the individual needs of a trainee. The adjustment capability of a logic scheme is determined by three characteristics:

- o <u>Speed of Response</u>. How quickly does difficulty level change to an appropriate value following a change in trainee performance?
- o <u>Progression/Regression</u>. Can the difficulty level "back-up" or can it only increase?
- o <u>Resolution</u>. How finely can difficulty level be adjusted - what is the least by which it can change?

It should be recognized that some overlap into other aspects of the training situation exists. Speed of Response is affected by the method of performance measurement and Resolution may be limited by the adaptive variable.

In each of two previous studies (Wood, 1969; Lowes et al., 1968), widely differing adaptive logic schemes have been compared. The automatic, machine controlled logic provided both progression and regression with nearly infinite resolution in response to instantaneous error. For the control groups the manual logic limited changes in difficulty to progression only through a relatively few steps according to a pre-established time schedule. The present study examined two somewhat less extreme schemes explained in the following paragraphs.

Figure 2 shows the basic elements of an adaptive training situation in which system error is taken as indicative of trainee performance. It can be seen that the error comes from two sources; the trainee/aircraft and the disturbance. The error source of interest is the trainee/aircraft. A means for reducing the influence of the disturbance is needed.

One way to control for the disturbance is to use a disturbance generator which has constant statistical properties for a period equal to the length of a trial. Differences in error scores between trials are then due only to changes in trainee performance. This approach has the disadvantage that speed of response is slow. An alternative is to shape the disturbance spectrum to permit a shorter measurement interval.

If the disturbance is passed through a high pass filter with a time constant of, for example, 5 sec. and the error is filtered through a low pass filter with a 5 sec. time constant, the filtered error should reflect mostly trainee/aircraft performance

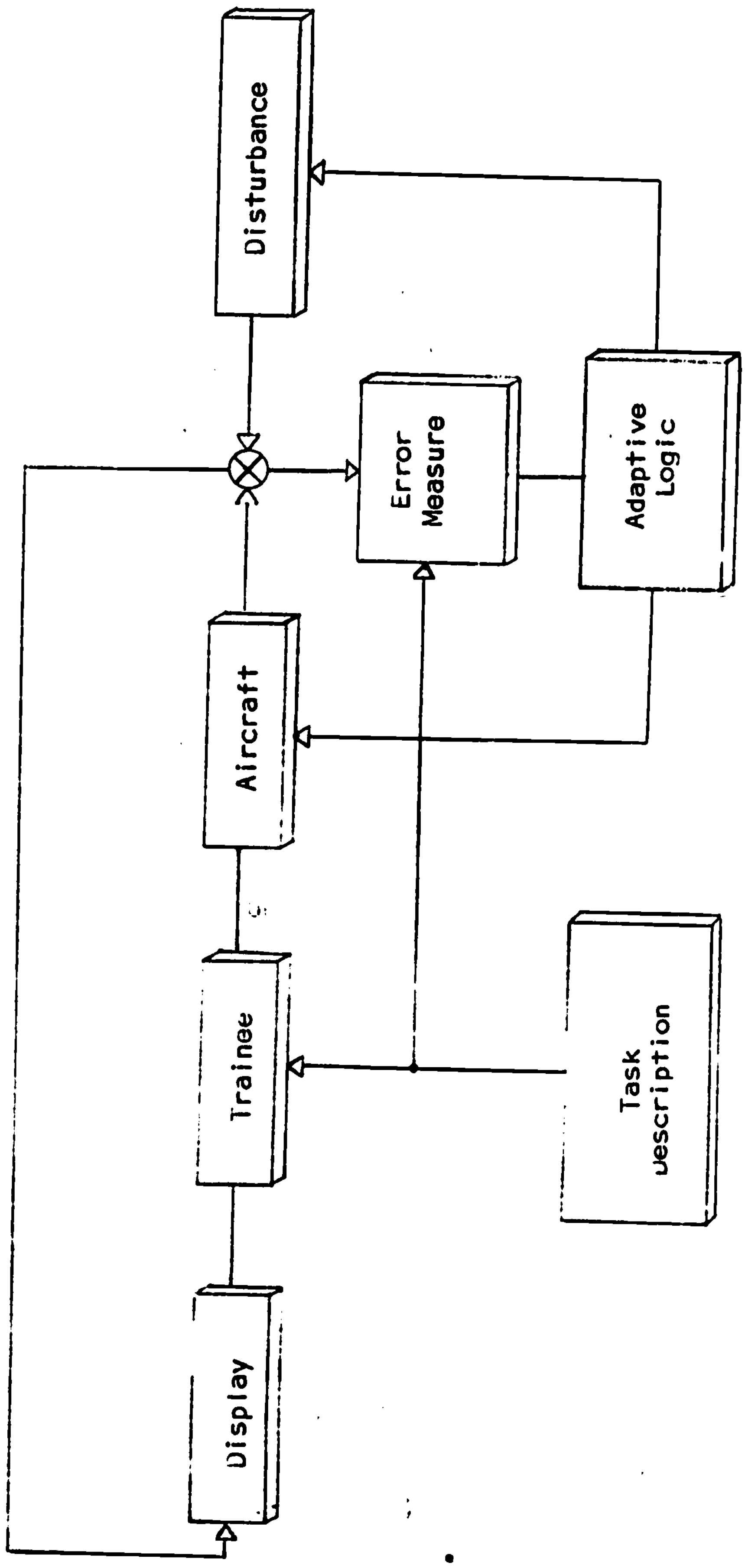


Figure 2. Illustration of Adaptive Training Situation

with little influence from the disturbance. The low pass filter might be thought of as averaging the error over a 5 sec. interval. The high pass filter progressively attenuates disturbances with periods increasingly longer than 5 sec. This shaped-spectrum, filtered-error scheme has the advantage of fairly rapid response with less influence by the disturbance than instantaneous error.

For automatic adaptation in the present study, difficulty level was obtained as a function of filtered error in an identical manner to that employed by previously cited investigators who obtained difficulty level as a function of instantaneous error. That is, the instantaneous change in difficulty level was proportional to an error tolerance minus the filtered error. Manual adaptation increased difficulty in steps based on error averaged over a 2 min. trial.

A comparison of Automatic and Manual adaptation with non-adaptation (constant difficulty) is shown in Table 4. Two additional differences between Automatic and Manual, as defined for this experiment, should be noted. First, for the Automatic group the first trial was begun with the criterion level of difficulty. Since a characteristic of the adaptive scheme is that difficulty level can be reduced much faster than it can be increased, the difficulty level was expected to move to an appropriate level (anticipated to be less than criterion) within a few seconds. For succeeding trials, the initial difficulty level was taken to be the average difficulty level of the previous trial.

The second characteristic difference was the capability for automatically adjusted difficulty to exceed the criterion level. This is seen as one of the advantages of automatic adjustment; the ability to match brief periods of excellent performance with an appropriately challenging task. A second feature of this ability is that it allows a definition of task mastery for the Automatic group equivalent to that for the Manual group, as discussed below.

Under Automatic adaptation, difficulty level varies continuously within a trial to hold error constant while for Manual adaptation, difficulty is fixed during a trial and error varies. Performance under the two conditions is equivalent when average error under fixed difficulty and average difficulty under fixed error both meet the respective criteria. For illustration, let 1.0° be the criterion error for Automatic adaptation and let the fixed task be at 100% difficulty. Then two trials in succession on the Automatic task for which the average difficulty level equals or exceeds 100% represents equivalent performance to two trials in succession on the fixed task with 1.0° or less average error.

TABLE 4. COMPARISON OF ADAPTIVE SCHEMES

	INITIAL DIFFICULTY LEVEL	DIRECTION OF CHANGE	NUMBER OF LEVELS	MAX'MUM DIFFICULTY	PERFORMANCE MEASUREMENT INTERVAL	FREQUENCY OF LEVEL CHANGE	ERROR BEHAVIOR
AUTOMATIC	Criterion	Progression and Regression	Infinite	Greater Than Criterion	Approximately Five Seconds	Continuous	Essentially Constant
MANUAL	Low	Progression Only	Four Steps	Criterion	Two Minutes	Integral Multiples of Two Minutes	Variable
CONTROL	Criterion	None	One	Criterion	Two Minutes	None	Variable

Manual adaptation was limited to 4 steps to minimize the chances of experimental artifact, as mentioned in Section I.

3.1 FORCING FUNCTION AMPLITUDE AND ADAPTIVE LOGIC. If the two filters mentioned above do not cut off sharply, difficulty level will be affected directly by the disturbance. When Forcing Function Amplitude is the adaptive variable, a second error nulling loop in parallel with the trainee/aircraft will be formed by the error measure, adaptive logic and disturbance. If the adaptive logic is too sensitive, too much error reduction will be accomplished by adjustment of the disturbance and the trainee will not be allowed to work his way out of large error situations.

Reduction in the sensitivity of the adaptive logic may be accomplished by reducing the gain (change in difficulty per unit error difference from criterion), the technique used in previous studies, or by extending the performance measurement interval. It is in respect to the latter approach that the automatic and manual logic in the present experiment are on a continuum.

Regardless of the gain or performance measurement interval, the difficulty level will adjust to a non-zero value if the trainee stops trying to fly. In fact, with the trainee completely out of the system, the difficulty level will seek that value which will cause the disturbance to meet the error criterion. Thus, difficulty level will not accurately reflect trainee skill at low levels of difficulty.

4. EQUATING VARIABLES WITH RESPECT TO DIFFICULTY

If a fair comparison of the adaptive variables is to be made, they must be equated in such a way that a given difficulty level, as determined by the adaptive logic, produces equivalent difficulty of practice for each of the variables. Otherwise, the effect will be to constrain the relative range of difficulty of the variables.

A pilot study was performed which demonstrated no substantial differences in performance between adaptive variables as a function of difficulty level. In the study, four subjects practiced on each of the three adaptive variables, adapted automatically, and the criterion level control condition. Treatment conditions changed each trial in a fully counterbalanced sequence. It was assumed that if difficulty level was found to progress in approximately the same manner for all three variables, they were essentially equivalent in difficulty at any given level. This was assumed to follow from the basic assumption that increases in difficulty level will follow a steady growth in trainee skill.

5. DETAILS OF THE EXPERIMENT

5.1 SUBJECTS. One hundred four volunteers attending colleges in the Orlando, Florida area served as subjects. All subjects were right handed males between 18 and 25 years of age capable of reading Jaeger No. 1 binocularly. Subjects with vision correctable to this standard were accepted if they wore contact lenses or if the frames of their glasses were narrow enough to fit inside the viewing hood of the experimental apparatus. Subjects were compensated for participation in the experiment.

5.2 EXPERIMENTAL APPARATUS. The task required the subject to keep a horizontal line centered on the screen of a 5 in. oscilloscope. An extended viewing hood maintained the viewing distance at a nominal 34 cm.; deviations were a result of variations in subjects' facial contours. A field of view of $\pm$ 11° was afforded with 1 cm. on the screen corresponding to 1.69° visual angle. A graticule scribed with the recommended aircraft symbol for heads-up-displays (Ketchel & Jenny, 1968) was used. With the display representing a heads-up, through-the-windscreen view of the horizon, 1° visual angle corresponded to 1° aircraft pitch angle. A pedestal permitted the scope to be raised or lowered to accommodate eye heights between 26 and 42 inches.

Subject control inputs were made through a two-axis side-arm controller mounted on a student chair in place of the writing surface. The lateral axis was locked. The grip was a contoured handle adapted from a search-light control and projected 6 in. above the mounting surface. Maximum deflection was $\pm$ 2.5 in. with a force gradient of 0.375 lb/in. Mass and friction were such that the natural frequency and damping ratio of the stick were 32.5 rad/sec and 0.19, respectively.

The simulated aircraft dynamics, adaptive logic and scoring were programmed on the REAC 400 Analog Computer at the Naval Training Device Center Computer Laboratory. A block diagram of the program is shown in Figure 3. As mentioned previously, the short period approximation of the pitch angle response was used. The overall transfer function relating the display output, O(s) to the control input, I(s), was:

$$\frac{O(s)}{I(s)} = \frac{k(T_{\theta 2}s+1)}{s(s^2/\omega^2 + 2\zeta s/\omega + 1)}$$

Under all conditions ζ was constant at 0.7. For the transfer task, condition XF, k was 16 deg visual angle/in. stick deflection/sec.; $T_{\theta 2}$ was 0.486 sec. and ω was 1.0 rad/sec. These values were selected to give the same effective time constant (0.315 sec.) as the criterion level of the training task. At the criterion (100%) level of the training task, corresponding to the Criterion condition CR, k was the same as for XF but $T_{\theta 2}$ was zero and ω was 2.5 rad/sec.

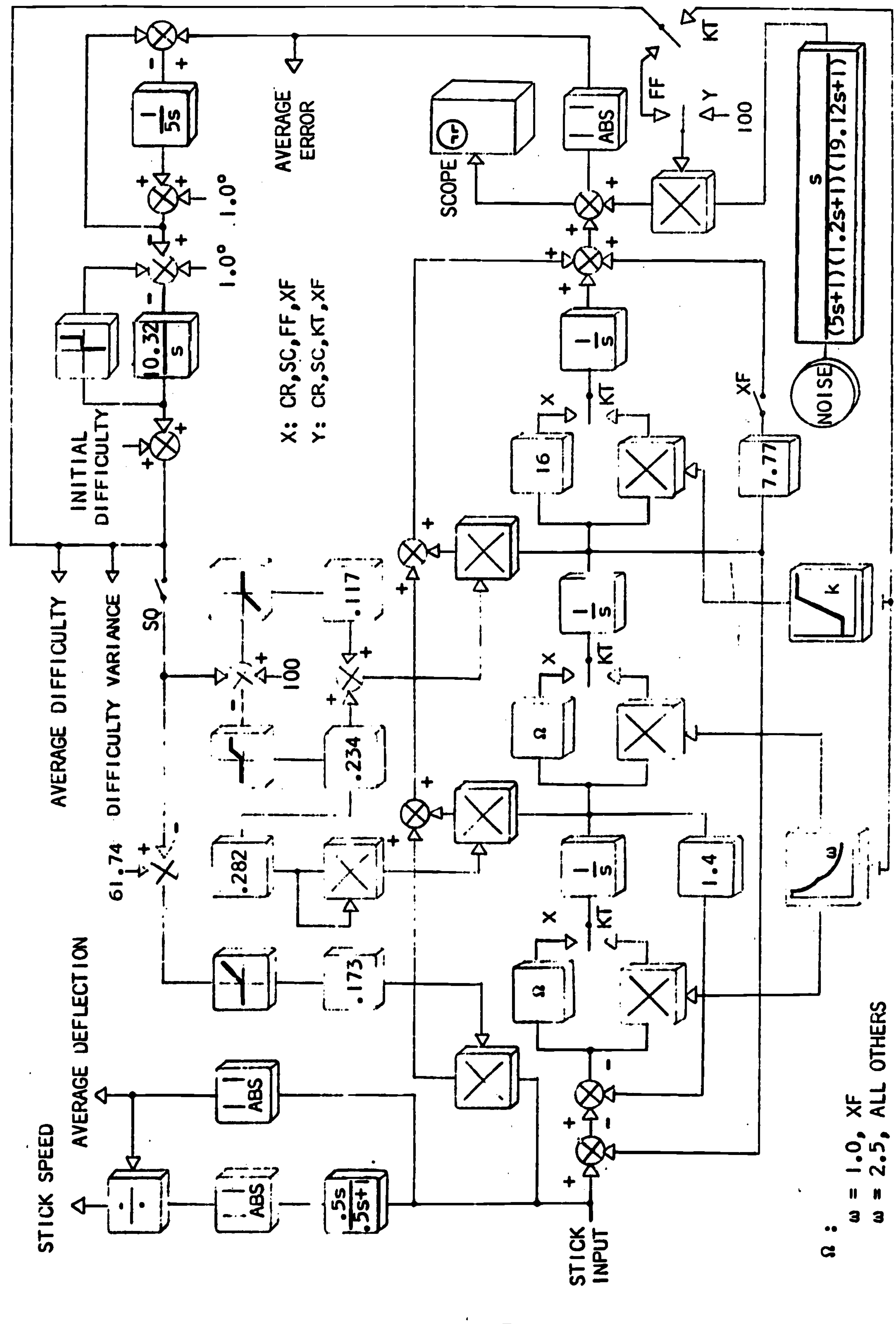


Figure 3. Block Diagram of Experimenta. Training Task

For Automatic and Manual System Compensation (ASC and MSC, respectively), the transfer function was the same as for CR with the addition of variable feed-forward to form a third order lead:

$$\frac{O(s)}{I(s)} = \frac{k}{s(s^2/\omega^2 + 2\zeta\, s/\omega + 1)}\left[C\,(s^3/k\omega^2+2\zeta s^2/k\omega+s/k)+B(s^2/k\omega)+A(s/k)+1\right]$$

The variation of A, B, and C with difficulty level so as to compensate the system as discussed in Paragraph 2.3 is presented in Table 5. At 100% difficulty, A, B and C were all zero so that a system identical to condition CR resulted.

TABLE 5. SYSTEM COMPENSATION COEFFICIENTS

Difficulty Level (DL)	A	B	C
0-61.74%	8.96	6.38	0.173 (61.74-DL)
61.74 - 100%	0.234 (100-DL)	$(0.282A)^2$	0.0
100 - 174%	0.117 (100-DL)	0.0	0.0

Conditions AKT and MKT (Automatic and Manual Gain-Effective Time Constant product) had the same form of transfer function as CR but k and ω changed as a function of difficulty level as shown in Figure 4. The values shown in Figure 4 were derived from data for Experiment II of Matheny and Norman (1968) as follows.

Error for the first block of trials was plotted as a function of gain-effective time constant product (kt_e) and the best straight line fit was obtained. The equation for the line was then used to transform a plot of kt_e as a function of k and ω (for $\zeta = 0.7$) into error as a function of k and ω. From the transformation, k as a function of error for constant effective time constant was obtained as was ω as a function of error for constant gain. These data were then combined to form a plot of ω vs. error for increasing k and t_e constant at 0.2 sec. with k changing from 4 to 16. The plot was continued for increasing error with k constant at 16 and t_e increasing. Figure 4 was obtained by transforming error into difficulty level by equating the error corresponding to the values of ω and k for condition CR to 100% difficulty. Computer scaling considerations were the principal constraints placed upon the range of values used.

Under the Automatic and Manual training variants of the Forcing Function Amplitude condition (AFF and MFF), the aircraft dynamics were identical with condition CR while the amplitude of the forcing function changed.

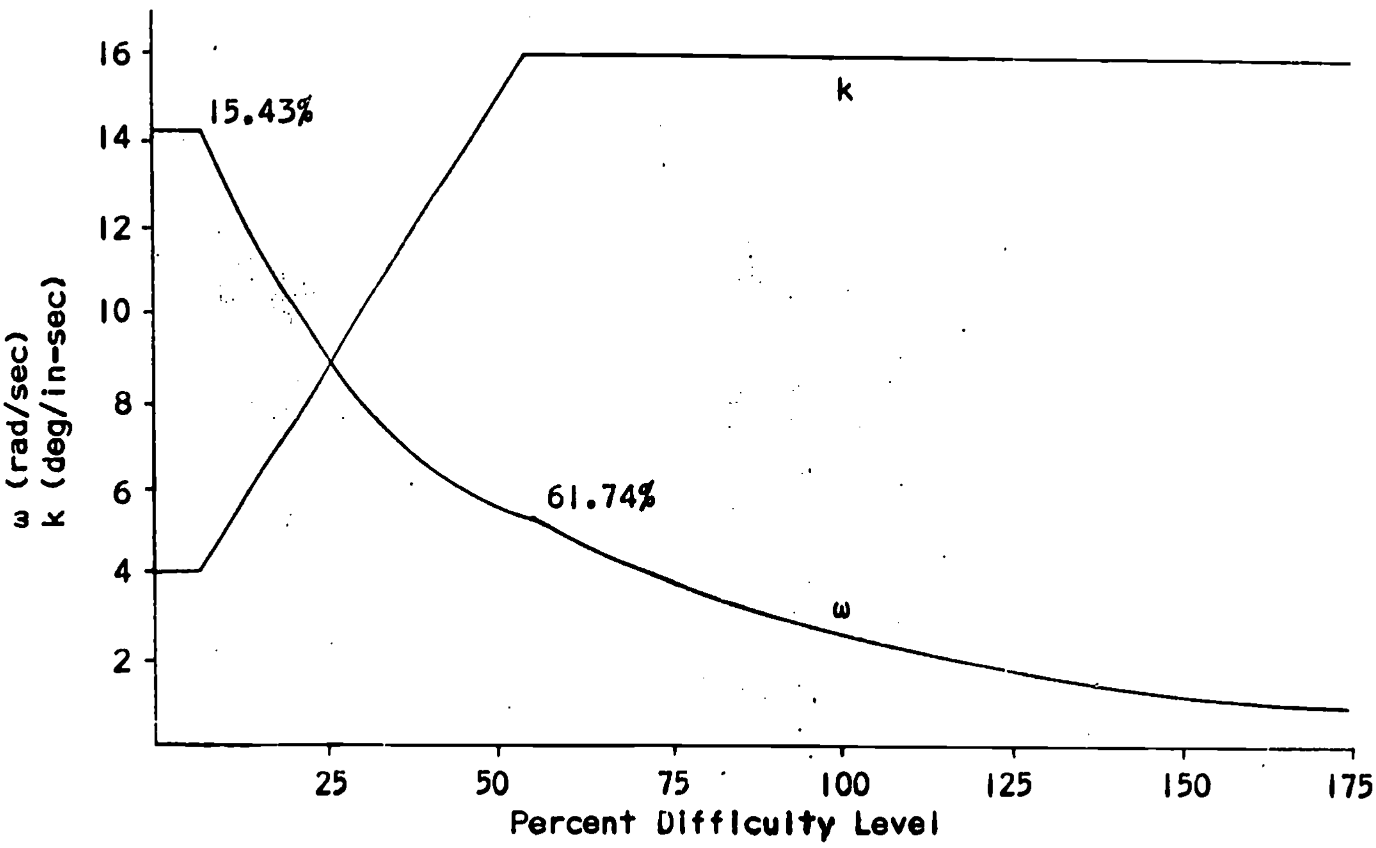


Figure 4. Variation of k and ω as a Function of Difficulty

For all conditions except AFF and MFF, including XF, the forcing function amplitude remained constant at the 100% level. At the 100% level, the forcing function alone, without attempt on the part of a subject to null the error, produced an average absolute error of 2.0°. Standard deviation across trials was 0.16°. If, under condition AFF, no attempt was made to null the error, an average difficulty level of 58.9% (standard deviation 1%) resulted. Preliminary experimentation established that this level of forcing function produced a task for which most subjects could meet the required average error criterion (1.0°) within one hour of practice. (A level for which the error produced by the forcing function alone was 3.0° made the task too difficult to master in one hour.)

As indicated in Figure 3, the forcing function was the filtered output of a "white" noise source. The noise source used a 12 bit shift register with pseudo-random bit code clocked at 34 Hz to produce a 2 min. repetition interval. The unfiltered power spectrum was essentially flat to 16 rad/sec. The original form of the filter provided a bandpass between 0.2 and 0.83 rad/sec but tests with preliminary subjects indicated a need for a less difficult disturbance. The addition

of the 19 sec. lag increased the low frequency content and reduced the equivalent bandwidth to 0.6 rad/sec (determined in the manner suggested by Elkind, 1964). The additional lag made the task easier but negated to some extent the attempt to reduce the direct influence of the forcing function on the difficulty level, as discussed in Paragraph 3.

The adaptive logic for the Automatic training conditions shown in Figure 3 adjusted the difficulty level to maintain 1.0° average absolute error. After the absolute error was filtered through a first order lag with a 5 sec. time constant, it was compared with the 1.0° reference and the difficulty adjusted appropriately:

$$\% \text{ Difficulty} = 10.32 \int (1.0 - E)\, dt + \text{IDL}$$

where E is the filtered absolute error and IDL is the initial difficulty level. The 1.0° initial condition on the filter shown in Figure 3 is necessary in order to insure that difficulty does not change until error values begin to pass through the filter. The difficulty level was limited to values between 0 and 174%.

The three levels of difficulty for Manual adaptation were 30.87% for level I, 61.74% for level II and 80.86% for level III. The final level was 100%, identical with condition CR.

Performance measures consisted of the average absolute error (degrees visual angle), the mean and variance of the difficulty level, the mean absolute stick deflection (inches) and a measure of the speed of stick movement.

The stick speed measure was developed because Lowes et al. (1968) found neither the mean nor variance of stick deflection to be sensitive to variations in control technique. Data presented by Krendel (1952) showed the control input power spectrum of a subject to increase the energy input between 4 and 10 rad/sec with practice. As shown in Figure 3, an approximation to the control input power spectrum was obtained by dividing the absolute mean of the stick inputs filtered through a 2 rad/sec high-pass filter by the mean absolute stick deflection. It was expected that the result would be the proportion of energy in the control inputs above 2 rad/sec. For reasons not fully understood, it was possible for subjects adopting a bang-bang type control strategy to produce a quotient greater than unity. The measure was, therefore, taken as merely indicative of the speed or quickness of stick movements.

5.3 PROCEDURE. Subjects were assigned randomly, eight to each of the eight conditions. Subjects were afforded a minimum of 16 trials within which to complete the experiment before being classified as failures. When scheduling of subsequent subjects did not conflict, potential failures were given additional time to complete the experiment.

Each trial was 2 min. long with a 2 min. rest between blocks of 4 trials. This schedule was followed independently of subjects meeting criteria for a change of conditions, except that testing ended when a subject performed to the required standard for completion of the experiment. To maintain a relatively constant inter-trial interval of approximately 35 sec., the experimenter shammed the recording of the mean and variance of difficulty level and the setting of the new initial difficulty level for the Manual adaptation and Criterion control training conditions.

For the first trial for each subject trained under Automatic adaptation the initial difficulty level was set at 100%. On subsequent trials the initial difficulty was set to the average difficulty of the previous trial. When a subject completed two trials in succession with an average difficulty level equal to or greater than 100% he was transferred to condition XF. Practice on condition XF was continued until two trials in succession with 1.0° or less error were performed.

Manually adapted subjects began practice at difficulty level I and advanced to a succeeding level whenever they performed one trial with 1.0° or less error. They practiced condition CR until they performed two trials in succession with 1.0° or less error, then transferred to XF which they practiced until the same criterion was reached.

The CR control group practiced condition CR to the two trials with 1.0° or less criterion, then transferred to XF for practice to the same criterion. The XF control group simply practiced condition XF to the error criterion.

Prior to the first trial subjects received the vision test and read the instructions (see Appendix A). The instructions emphasized the type of stick movements required and the relation between stick movements and the movement of the line.

Subjects were given no informative feedback about their progress through the experiment. If they asked how they were doing, they were told "well" or "pretty good".

Trials and breaks were timed automatically. Performance measures were recorded manually to four significant figures from a digital voltmeter.

A daily dynamic check of the equipment was performed using an autopilot.

6. PLANNED ANALYSES OF THE DATA

The principal analyses planned for this experiment were a comparison of trials to criterion on the training task for each group using the CR group as a reference and trials to criterion on the transfer task with the XF group as reference. It was expected that:

- o All Manual and Automatic conditions would require significantly fewer trials than the control groups to reach criterion.

- o The Automatic groups would require significantly fewer trials to reach criterion than would the Manual groups.

- o One of the adaptive variables would emerge as requiring significantly fewer trials in either training or transfer or both.

Subsidiary comparisons were planned primarily to shed light upon the pilot rating vs. gain-time constant product question raised in Paragraph 2.1. It was expected that both error scores and control input measures would have to be compared for the last training and first transfer trials.

Since pilot ratings could not be taken from the inexperienced subjects, it was expected that control input measures could be used instead. The work of Bird (1963) suggested that increases in stick force required for a given task produce decreases in pilot ratings. For a linear, spring-centered stick, larger deflections would require higher stick forces, hence pilot opinion should be inversely related to mean stick deflection.

For comparison of the performance of all training groups on the last training and first transfer trials, the error scores were expected to be:

- o The same on the basis of equivalent gain-effective time constant products; or,

- o Different, with those for the first transfer trial larger because of the lower pilot rating associated with the transfer condition.

Furthermore, from the lower associated pilot rating, the transfer task was expected to require larger average stick deflections.

While comparison of stick speed scores between tasks was planned, no outcome was predicted.

Because all experimental groups were trained to the same criterion prior to transfer, no differences among groups on the last training trial were expected for any measure. Differences among groups on any of the measures for the first transfer trial would be the result of differential effects of method of training upon transfer.

SECTION IV

RESULTS

The results of the experiment have been separated into those bearing on the primary questions of the study and those relating to the subsidiary questions.

I. PRIMARY QUESTIONS

The mean trials to criterion for each group for the training and transfer tasks are shown in Table 6.

TABLE 6. MEAN TRIALS TO CRITERION

	ASQ	AKT	AFF	MSQ	MKT	MFF	CR	XF
TRAINING	7.25	6.62	5.00	11.38	7.50	7.50	5.88	-
TRANSFER	3.88	2.75	4.00	5.50	3.62	2.38	4.50	7.62

Percent of positive transfer was computed according to the formula:

$$\frac{C - E}{C} \times 100\%$$

Where C and E are the number of trials required by the XF control group and one of the experimental groups, respectively. The percentages are shown in Table 7.

TABLE 7. PERCENT POSITIVE TRANSFER

MFF	AKT	MKT	ASC	AFF	CR	MSC
68.8	63.9	52.5	49.1	47.5	40.9	27.8

Miller's many-one test (Miller, 1966, p. 167) was used to compare the CR group, as a control group for training, with the other six groups on trials to criterion on the training task. With a critical value for the difference in mean ranks of 21.28 ($P < .05$), only the MSC group required significantly more training trials than the control. The mean ranks for the groups are given in Table 8.

TABLE 8. MEANS OF RANKS FOR ORIGINAL TRAINING GROUPS

MSC	ASC	AKT	MFF	AKT	CR	AFF
46.8	30.31	29.06	28.06	27.50	21.63	16.25

The same test was used on trials to criterion on the transfer task, with the XF group as control. A critical value for the difference in mean ranks of 24.67 ($P < .05$) showed the MFF, MKT and AKT groups to require significantly fewer transfer trials than the control, indicating significant positive transfer. Table 9 shows the mean ranks for the groups on the transfer task.

TABLE 9. MEANS OF RANKS FOR TRANSFER TASK GROUPS

XF	MSC	CR	ASC	AFF	MKT	AKT	MFF
52.81	40.63	34.69	32.25	31.44	25.19	23.13	19.88

Because of a large number of failures, it was necessary to test 40 more subjects than the 64 necessary to complete the experimental design. The distribution of failures by experimental condition is shown in Table 10. Most failures were given 1 to 7 additional trials beyond the minimum of 16 trials for completion of the experiment.

TABLE 10. DISTRIBUTION OF FAILURES BY GROUPS

XF	MKT	AFF	MFF	CR	AKT	MSC	ASC
0	2	3	4	5	5	8	13

A test on the distribution of failures gave a significant χ^2 (22.4, $p < .01$) indicating a non-chance concentration of failures under the ASC and MSC conditions.

1.1 MSC FAILURES. Because the data showed 7 of the 8 failures under the MSC condition to have advanced only to the CR level of the training task at the time of failure, tests were made to determine whether positive transfer to the CR level took place from lower levels of the MSC condition.

First, it was determined that subjects passing the MSC condition did not spend a significantly different amount of time at levels I, II, and III than did failing subjects. Failing subjects spent a mean of 3.43 trials at those levels (combined total) while passing subjects averaged 3.75. A Mann-Whitney test gave a U of 25.5 with p (7,8) < .389.

Using the CR group as a control, the transfer from lower levels to the CR level was determined for each Manually adapted group on the basis of trials to criterion. (Automatic groups could not be tested because there was no record of the time spent at various levels.) These data are shown in Table 11.

TABLE 11. MEAN TRIALS AT CR AND PERCENT TRANSFER

	CR	MSC	MFF	MKT
TRIALS	5.88	7.63	4.00	3.72
PERCENT	-	- 29.8	32.0	36.2

A Miller's many-one test was not significant at conventionally accepted levels (critical value for a difference in mean ranks of 11.02) for comparison of the groups with the CR control. The mean ranks are summarized in Table 12.

TABLE 12. MEAN OF RANKS FOR TRANSFER TO CR

CR	MSC	MFF	MKT
20.38	22.75	11.82	11.07

Since the experiment had not been designed to test for differences in transfer to level CR, it was decided to relax the experimentwise requirement for statistical significance and perform further tests.

A Kruskal-Wallis analysis of variance by ranks, corrected for ties, was significant ($H = 9.23$, $p < .05$). Mann-Whitney tests, for 8 in each group, were significant for MKT vs. CR ($U = 14$, $p = .032$) and MFF vs. CR ($U = 10.5$, $p = .012$) but not for MSC vs. CR ($U = 23.5$, $p = .206$). It appears that practice at low levels of MSC provides, at most, zero transfer to level CR while for MFF and MKT the transfer is significantly positive.

Table 13 provides some indication of why MFF and MKT show positive transfer and why MSC has poor transfer and a high failure rate. The table shows the mean stick speed score on trials when the 1.0° error criterion was satisfied for levels I, II, III, and CR for those individuals passing MFF, MKT and MSC and for those failing MSC. Mean performance at level CR on those trials for which the error criterion was not satisfied is also shown. Note that the latter constitutes the bulk of practice at CR for the MSC failures.

From the table data, it appears that MSC subjects start low and build up their scores as a function of changes in level. The MSC failures are always lowest and appear to perseverate in an inappropriate technique which ultimately leads to failure.

TABLE 13. MEAN STICK SPEED × 100

	MFF	MKT	MSC (Pass)	MSC (Fail)
I	82.31	87.00	67.00	62.25
II	83.58	88.85	78.06	74.09
III	83.39	89.58	83.68	81.78
CR (Pass)	85.29	86.97	83.93	80.26
CR (Fail)	82.15	80.52	83.16	76.74

2. SUBSIDIARY QUESTIONS

Since both subsidiary questions involve the two control input measures, these measures, as well as the error data, are discussed in individual sections following.

2.1 STICK DEFLECTION. A Split-Plot Factorial 7.2 Analysis of Variance (Kirk, 1968) was used to test for differences among the seven training groups on the last training trial and the first transfer trial.

The original data proved to be heterogeneous when tested with the F max test. An examination of ranges indicated a reciprocal transformation would be appropriate and this transformation was applied to the data.

Table 14 is a summary of the ANOV of the transformed stick deflection data.

Because the AB interaction was significant the simple main effects were analyzed. Results of this analysis indicated a significant difference among the groups on the last training trial ($p < .01$) but no significant differences among the groups on the first transfer trial.

A separate analysis of deflection scores on the last training trial showed the AKT group to have the highest mean score, which was significantly different from scores of the CR and ASC groups ($p < .01$) but not statistically different from any of the remaining groups.

TABLE 14. ANOV OF STICK DEFLECTIONS

Source	df	MS	F	P
BETWEEN SUBJECTS	55			
A (groups)	6	.0022	2.00	NS
SUBJECTS WITHIN GROUPS	49	.0011		
WITHIN SUBJECTS	56			
B (trials)	1	.0162	81.00	.01
AB	6	.0010	5.00	.01
B × SUBJECTS WITHIN GROUPS	49	.0002		

Comparing stick deflection scores of the groups' last training trial with their first transfer trial indicated statistically significant differences.

Table 15 represents the means of stick deflection scores for the seven groups.

TABLE 15. MEAN STICK DEFLECTION SCORES, INCHES

	ASC	AKT	AFF**	MSC**	MKT**	MFF**	CR**
Last Training Trial	0.104	0.199	0.118	0.122	0.133	0.118	0.111
First Transfer Trial	0.122	0.191	0.172	0.186	0.199	0.182	0.247

** Differences of mean scores, last training and first transfer trials significant $p < .01$.

As can be seen in the table, all the groups showed significant increases in stick deflection scores from the last training to the first transfer trial with the exception of the ASC and AKT groups.

2.2 STICK SPEED. Table 16 is a summary of the ANOV of stick speed scores for the seven training groups on the last training and first transfer trial.

TABLE 16. ANOV OF STICK SPEED SCORES

Source	df	MS	F	P
BETWEEN SUBJECTS	55			
A (groups)	6	65.98	.37	NS
SUBJECTS WITHIN GROUPS	49	177.35		
WITHIN SUBJECTS	56			
B (trials)	1	280.21	12.30	.01
AB		37.87	1.66	NS
B × SUBJECTS WITHIN GROUPS	49	22.78		

An F max test indicated the data were homogeneous. As the table indicates, the only significant F was the difference between trials. However, the small F (.37) for the main effect of A was examined further by a completely randomized ANOV (Kirk, 1968) on data from the first training trial and the last training trial. The main interest was not in significance, per se. Rather the Between group and Within group mean squares were examined to determine whether the F test on the first transfer trial would be at or above unity since this was not the case in analyzing data on the last training and first transfer trials. The ANOV yielded an $F = 3.76$ ($p < .01$). The Within group term (the error term) remained substantially the same in the ANOVs of the remaining trials while the Between group term decreased. This was taken to mean that the means for the groups were becoming more similar as training progressed while the variability of the groups was rather stable.

As to stick speed differences on the last training and first transfer trials, perusal of the data indicates higher mean speed scores on the last training trial than on the first transfer trial.

2.3 ERROR SCORES. In order to make valid comparisons between the last training and first transfer trials for the Automatic groups it was necessary to adjust their error scores because these groups could exceed a difficulty level of 100% on the last training trial. Consequently, error scores for these groups were adjusted to an equivalent error score for a 100% difficulty level by dividing the error score by the attained average difficulty level and then multiplying the quotient by 100% for each subject in the three Automatic groups.

The data for error scores proved to be heterogeneous and a reciprocal transformation was indicated as a result of an examination of ranges.

Table 17 summarizes the ANOV for the transformed error scores.

TABLE 17. ANOV OF ERROR SCORES

Source	df	MS	F	P
BETWEEN SUBJECTS	55			
A (groups)	6	.0002	1.00	NS
SUBJECTS WITHIN GROUPS	49	.0002		
WITHIN SUBJECTS	56			
B (trials)	1	.0020	20.00	.01
AB	6	.0005	5.00	.01
B × SUBJECTS WITHIN GROUPS	49	.0001		

Simple main effects were analyzed and the results indicated a significant difference between groups (A) on the first transfer trial ($p < .05$). (Table 18)

In addition significant differences were noted between the two trials for the Automatic System Compensation (ASC) group ($p < .05$) and the Criterion control (CR) group ($p < .01$).

Table 18 shows the mean scores for the groups on the trials.

TABLE 18. MEAN ERROR SCORES, DEGREES

	ASC*	AKT	AFF	MSC	MKT	MFF	CR**
LAST TRAINING TRIAL	0.948	0.860	0.927	0.931	0.830	0.860	0.830
FIRST TRANSFER TRIAL	1.038	0.901	0.990	0.977	0.884	0.924	1.092

* Difference between means on two trials are Significant $p < .05$

** $p < .01$

2.4 DATA SUMMARY. Table 19 combines the results of the several analyses for speed, deflection and error scores on the last training and first transfer trials for the seven groups.

TABLE 19. SUMMARY OF DATA: MEAN SCORES

	LAST TRAINING TRIAL			FIRST TRANSFER TRIAL		
	SPEED × 100	DEFLECTION INCHES	ERROR DEGREES	SPEED × 100	DEFLECTION INCHES	ERROR DEGREES
ASC	83.03	0.104	0.948	82.63	0.122	1.038
AKT	87.05	0.199	0.860	87.31	0.191	0.901
AFF	87.12	0.118	0.927	80.89	0.172	0.990
MSC	83.64	0.122	0.931	83.42	0.186	0.977
MKT	89.73	0.133	0.830	85.03	0.199	0.884
MFF	85.68	0.118	0.860	78.81	0.182	0.924
CR	85.45	0.111	0.830	81.68	0.247	1.092

SECTION V

DISCUSSION AND CONCLUSIONS

1. SUMMARY

From the results presented in the preceding section, the following conclusions have been drawn with respect to the single axis task used in this study:

- On balance, Manual adaptation as used here is slightly superior to Automatic adaptation, but this could be a function of the difference in performance measurement intervals.

- Gain-Effective Time Constant product is slightly superior to Forcing Function Amplitude as an adaptive variable.

- System Compensation, as implemented for this experiment, is not a satisfactory adaptive variable. With modification of principle, however, it may be possible to make it satisfactory.

- Aiding and quickening, as conventionally conceived, are not satisfactory adaptive variables.

- A performance measurement interval longer than 5 seconds should be used as a basis for adjusting task difficulty.

- Gain-Effective Time Constant product is not suitable as a measure of the perceptual fidelity of simulation.

- Potential adaptive variables should be tested for positive transfer from lower to higher levels of difficulty after only small amounts of practice.

- Instructions to subjects may suggest patterns of control movement which are not equally suited to all treatment conditions. Some subjects may be led to initially use inappropriate control techniques.

- Subjects do not require informative feedback concerning performance in order to develop increased skill at the task.

- The general applicability of the results are limited, to an unknown extent, by the atypical nature of the simulated aircraft transfer functions.

Support for these conclusions in the data are presented in the following paragraphs.

2. SPECIFIC FINDINGS OF THE EXPERIMENT

2.1 MANUAL VS. AUTOMATIC. Because two of the three treatment conditions showing significant positive transfer were manually adapted, it is concluded that Manual adaptation is slightly superior to Automatic. This conclusion should, however, be qualified in light of the discussion in Paragraph 3.1 of Section III. There it was pointed out that adaptive logic made too sensitive to error by a short performance measurement interval would not afford the trainee much practice under large error situations. It seems reasonable to hypothesize that the reason Automatic adaptation of Forcing Function Amplitude did not show significant positive transfer, whereas the corresponding Manual condition did, is a result of the comparatively short performance measurement interval associated with Automatic adaptation.

2.2 ADAPTIVE VARIABLES. Gain-Effective Time Constant product is concluded to be the best adaptive variable of the three studied here because:

- Both the Automatic and Manual groups had significant positive transfer.
- The Automatic and Manual groups transferred with no significant change in error scores.
- The Automatic group transferred with no significant change in required stick deflection.

Forcing Function Amplitude is considered slightly inferior because only the Manual condition showed positive transfer and that was accompanied by a significant increase in average stick deflection.

2.3 SYSTEM COMPENSATION. As defined for this study, System Compensation is unsatisfactory as an adaptive variable for the following reasons:

- The large number of failures.
- The significantly greater number of training trials required by the Manual Group.
- The significant increase in error upon transfer for the Automatic group.
- The essentially zero transfer from levels I, II and III to condition CR.

In Paragraph 3 the condition will be discussed with respect to the reasons for it being unsatisfactory and how it might be modified into a workable method of training.

2.4 PERFORMANCE MEASUREMENT INTERVAL. The argument presented in 2.1 above applies. Longer performance measurement intervals allow the student more time to work his way out of a large error situation. With short measurement intervals the situation is somewhat like the notion that in flight training, the worse a student is, the less he gets to fly - the instructor most often has control.

2.5 FIDELITY OF SIMULATION. The criterion level of the training task and the transfer task had the same effective time constant (0.315 sec.) and the same gain-effective time constant product (5.04). Analyses of variance for performance on the last training and first transfer trials showed no differences between groups but a significant difference between trials for average error, average stick deflection and stick speed. It is, therefore, concluded that neither the effective time constant nor the gain-effective time constant product is a sufficient basis for assessing the perceptual fidelity of simulation. Account must be taken of required changes in control technique.

2.6 TESTING ADAPTIVE VARIABLES. Tatz (1964) cites data from Duncan (1953) and a well-designed experiment by Mandler (1954) as evidence that negative or zero transfer of training occurs only for small amounts of first task practice. Increasing first task training leads first to decreasing negative transfer then to increasing positive transfer for situations potentially producing negative transfer.

In view of the preceding, the results of the present study showing essentially zero transfer from a progressively uncompensated system to a fully uncompensated system do not conflict with previous findings of positive transfer between quickened and unquickened systems. In the study by Holland and Henson (1956), subjects received a minimum of 93 min. 40 sec. training on the quickened system before transferring to the unquickened system. In the present study, manually trained subjects typically received 6 to 8 min. practice before all compensation was removed - apparently not enough for positive transfer.

Caution in adopting adaptive variables subject to comparatively rapid changes in level appears in order. A prudent course of action appears to be a test for positive transfer between successive steps of a candidate variable with only small amounts of practice at each level.

2.7 LIMITATION ON RESULTS. As noted in Section III, the aircraft transfer functions used in this study were compromised to permit the use of previously developed data and to allow subsidiary questions to be asked. The resulting functions are unlike those for any contemporary aircraft except possibly those employing direct lift control. The extent to which the unusual nature of these functions limits the findings concerning the three adaptive variables is simply unknown. The findings with respect to adaptive logic are, however, probably not substantially limited.

3. IMPLICATIONS FOR TEACHING CONTROL TECHNIQUE

Following an introduction to the study of operator behavior in terms of a describing function, this portion of the report takes those factors thought to contribute to the high failure rate on the System Compensation condition as points of departure for a discussion of the development of operator control technique.

3.1 BACKGROUND. Many experiments have been conducted to determine either qualitative or quantitative measures of the nature of the response pattern of the human operating various types of systems. From these studies it has been deduced that this response pattern (termed a describing function) is molded by the characteristics of the machine operated (called the controlled element or the plant dynamics) and by the task (forcing function) and performance criterion including instructions and constraints assigned to the man-machine system. For several reasons, including the analytical difficulty of securing an adequate mathematical description under different conditions, investigations have been limited to those in which the operators are experienced in performing the experimental task. The effect of such a selection process is to assure a certain degree of repeatability of the operator's response, thereby easing the data analysis task.

An examination of the transition of the operator's describing function as he progresses from the naive to the sophisticated in the required skill has not been reported if, in fact, it has been attempted. The design of the present study, as in any training situation, may be viewed as an attempt to shape the human describing function along certain lines. By analyzing the man-machine system as a servomechanism, certain interrelationships among the forcing function, the man, the performance criterion and the controlled element can be developed.

The subjects received no direct information concerning the level of their performance nor did they know what the criterion level of performance was. Thus, one can only speculate as to what criterion they may have set for themselves. Possible candidates are RMS error, error relative to mid-range frequency components of the forcing function, or error relative to ease of control stick manipulation. McRuer, Graham, Krendel and Reisener (1965) have indicated that unless otherwise instructed the operator appears to use RMS as a performance criterion since attempts to establish operator describing functions based upon the minimization of RMS error have been successful. Hence, it appears that as a first approximation one may assume that the operator will adopt describing function characteristics (i.e., mold his transfer function) to minimize RMS error.

The second principle of Birmingham and Taylor, cited previously in Section III, that the "transfer function required of the man [should be] ... no more complex than that of a simple amplifier" (1954a, p. 7) implies that the simplest behavior pattern for the human operator is that of making control movements directly proportional to the magnitude of the displayed variable. Given the forcing function and the performance criterion established in this study, the controlled element dynamics which call for exclusively proportional control behavior on the part of the operator are those of a rate or velocity control (i.e., a pure integration). If the assumption is made that the simplest control behavior pattern implies the least "difficulty" of system operation for the human a question arises concerning the ordinal arrangement of more complex control techniques according to difficulty level.

Control techniques may be broadly classified into three distinct categories: proportional (straight gain), averaging (lag) and anticipatory (lead). This is not to say that other control strategies such as a time-optimal, bang-bang control strategy may not be used. The concern here, however, is with the less complex types of control strategies.

It should be noted that the control technique required to attain a criterion level of performance may consist of one or a constant combination of two or more of the basic categories listed above. For example, one system may require only stick displacement proportional to all variations of the displayed error; another may require the stick displacement be proportional to the slow variations in displayed error but proportional only to the average value of more rapid variations of the displayed error. Still another system may call for the production of movements anticipatory of very slow variations of display movements, proportional to slightly faster variations and following only the mean of very rapid variations of the displayed error. Thus these systems call for techniques which are proportional (straight gain) in the first case, a combination of

straight gain and lag in the second, and a combination of anticipatory (lead), proportional (straight gain), and averaging (lag) in the third.

One might hypothesize that the greatest amount of transfer of training occurs when the performance criterion, forcing function and controlled element complex is such that the same grouping of categorical control techniques used on the training system can be used on the transfer system. It would also appear reasonable that there exists an optimum sequence of control strategy categories along which the operator can be trained to produce ultimately the technique required for successful operation of the transfer system. At the present time it does not appear that this optimum sequence is known - at least in an analytical sense. The utility of an adaptive training system could be presumed to be enhanced by the incorporation of the optimum sequencing of necessary control strategies into the adaptive logic scheme.

Such sequencing may be thought of as shaping the chaining of the operator's behavior. Since response chains are most efficiently constructed by training responses in reverse order to the sequence in which they will be used, the optimum sequencing of control strategies would probably be that which would build the operator's response chain in the proper order. What the chain of operator responses is for a given situation is not known, but the following hypothetical example is offered as an illustration.

Let the control movement required of the operator be a combination of techniques as discussed above. The combination would form a continuously repeated chain of behavior. If a combination of lag, straight gain and lead were required, the operator could be viewed as averaging high frequency components of the error (lag), making a control displacement proportional to the mean (straight gain) and then returning the control to neutral in anticipation of system response (lead) - all performed in a continuous cycle. Response elements in the chain would be established by the reinforcing effect of error reduction. Instructions to the subject calling for small error would presumably establish reduced RMS error as a reinforcer for those behaviors leading to error reduction.

3.2 CONTROL TECHNIQUES IN THIS STUDY. One means of varying the category of control technique necessary to achieve required performance criteria is to vary the form of the controlled element dynamics. Of the three training techniques used in this study (System Compensation, Forcing Function variation and Gain-Effective Time Constant variation) it appears that only System Compensation sufficiently altered the form of the controlled element so that more than one control style was necessary to successfully operate the machine as training progressed from initial run to transfer task.

A review of the power spectrum of the forcing function combined with the Bode plots which describe the variations of the controlled element indicates that the control techniques required both to produce a stable man-machine closed loop system and to reduce RMS error to the criterion level consist of low frequency proportional control plus mid-frequency lead for the following:

- The transfer condition.
- The Criterion training condition.
- The Forcing Function variation condition both Manual and Automatic except for very low levels of turbulence.
- All difficulty levels of the Gain-Effective Time Constant condition both Manual and Automatic.
- Only the higher levels of difficulty of the System Compensation condition, i.e., difficulty levels above level III of the Manual group.

Although the same grouping (i.e., straight gain - lead) of control techniques may be used for all of the situations listed above, it should be emphasized that the amount of gain and amount of lead necessary for satisfactory performance varies with the controlled element (i.e., either training element or transfer element) and with magnitude of the forcing function. Very notably absent in the above list are the System Compensation conditions at levels at or below training level III. Examination of the Bode plots of the controlled element for System Compensation below level III indicate that:

- Using a combination of gain and lead at or near level I is inappropriate, resulting in either system instability or large performance error.
- Using a combination of gain and lead at or near level II, while not necessarily destabilizing, does not significantly contribute to the reduction of system error with a given forcing function.
- The more appropriate control technique for level I would be the introduction of lag at mid frequencies with straight gain at low frequencies, while that for level II would be straight gain at all frequencies.

These observations indicate that under the System Compensation training condition, required operator control technique groupings change whereas they do not change for any other of the training procedures. Furthermore, the progression of groups appears to be inconsistent with the postulates made earlier that the optimum

sequencing of required control techniques would be one in which the simplest (i.e., straight gain) precedes the more complex. For System Compensation the simplest condition occurs at level II. It would appear that for the types of system compensation used in the System Compensation training procedure the sequence of control technique groupings which the operator must use to meet performance criterion do not train him to perform successfully on either the criterion or transfer conditions. The gain-lag combination can be used to effect stability on both the criterion and transfer tasks but only at the expense of increasing overall system error, so that, as a consequence, the performance criterion is not met.

Without specific and continuous measures of the operator's inputs it is impossible to do more than make an educated guess as to the form of compensation used by the operator. It is possible though deemed unlikely that other, more sophisticated forms of compensation were employed by the subjects in this study.

The stick speed score provides a rather gross determination of the type of system equalization used by the operator. The stick speed analyzer is discussed in Paragraph 5.2 in Section III. It gives a rough measure of the proportion of the pilot's stick input waveform which is composed of frequencies above 2 rad/sec. This is approximately the frequency at which stick power must be significantly concentrated in order to produce the form of lead necessary to meet the criteria of stabilization and RMS error mentioned previously for those training situations for which low frequency proportional control and mid-frequencylead are appropriate. For these situations the mean values of the stick speed for trials in which the RMS error criterion is met are in the range of 82-90 as shown earlier in Table 13. This indicates that a relatively large percent of the stick energy occurs above 2 rad/sec. By comparison speed scores for successful trials for levels I and II of the System Compensation condition lie in the 67-78 range, indicating the concentration of stick energy at lower frequencies. A stick speed analyzer which more sharply defined the relative energy spectra would better substantiate these observations. Such an analyzer would require a sharper cut-off than that used in this study. The optimum analyzer, of course, would divide the stick energy spectrum into many more bands than the two used here (above and below 2 rad/sec.) so that a more detailed picture of the power spectrum of the stick inputs could be obtained.

The rather high percentage of failures on the System Compensation Manual and Automatic conditions would appear to indicate that some vestige of training on lower levels of the System Compensation condition remain to influence control behavior on the criterion training task. That this may be the cause of failure is reflected in the speed scores. For those persons in the System Compensation group who failed the criterion task (and it was in the performance of this task that the great majority of System Compensation failures occurred) speed scores remained below 82. This would indicate

some failure to switch from the gain-lag control strategy learned in earlier training phases to the gain-lead control strategy necessary for the successful operation of the criterion task. In contrast, those persons who passed the criterion task in the System Compensation group were able to raise the speed scores to around 84 indicating the adoption of the necessary gain-lead technique in spite of the earlier training which they had received.

3.3 EFFECT OF INSTRUCTIONS. Examination of the instructions given to the subjects in this study should be made in light of the previously stated hypothesis that among the factors which mold the human operator response pattern are the instructions given to the operator. In order to expedite the achievement of adequate performance upon the experimental task some indication of the required control technique was given to the subjects. They were told (see Appendix A for complete instructions):

- "The stick controls the speed of movement of the line."
- To "make only small movements of the stick at first".
- To "pull the stick backward momentarily".
- "to think of 'bumping' or 'flicking' the stick".
- To "move the stick, release it, note the result and move again."

Although the subjects were not constrained to this type of operation it was intended to influence their control behavior pattern.

Following is a discussion of the information implicit in these statements. The first statement tells the subject that in general proportional control is not appropriate since a stick displacement proportional to the displayed error will cause a constantly increasing display movement. Consequently the magnitude of stick inputs should be proportional to the rate of change of display movements. The second statement ensures system stability. By the reduction of operator gain (i.e., making small movements of the stick) the man-machine system is stabilized using only the control law of the first statement without the necessity for introducing sophisticated techniques such as lag or lead equalization. The system error will, of course, be large until the subject masters the equalization technique necessary to ensure stability with a larger gain. The remaining statements indicate that the operator should adopt a pulsing type of behavior. According to McRuer, Hofmann, Jex, Moore, Phatak, Weir and Wolkovitch (1968) this is the control pattern necessary to achieve lead generation in a frequency range corresponding to what has been designated in the present study as the mid-frequency range.

The general tone of the instructions therefore was to encourage anticipatory (lead) control movement behavior. It should be recalled at this point that this type of behavior has been deemed adequate for most of the experimental conditions presented the subjects with the notable exception of the low difficulty levels of the System Compensation condition. This points to the possibility that the instructions given may have contributed, at least to some extent, to the difficulty of the subjects in the System Compensation training groups.

3.4 OPTIMAL SHAPING OF OPERATOR BEHAVIOR. In view of all of the problems presented by the System Compensation training procedure some suggestions for the useful modification of the technique as an adaptive training variable are in order. From the results obtained with the other two adaptive variables, it can be surmised that even relatively naive subjects can cope adequately with a system which requires the gain-lead control technique. A system which requires monotonically increasing functions of gain and lead equalization is illustrated by increasing difficulty levels of the Gain-Effective Time Constant condition. The operator learns sequentially the proper amount of gain for the system and the proper amount of lead. This is achieved by initially a simultaneous increase in system gain and a decrease in system natural frequency in the proper ratios and secondly, after criterion system gain has been reached, by reducing only system natural frequency.

In order to synthesize a system which molds the operator's behavior it would be well to abandon the conventional methods of aiding and quickening. A simple high gain feedback loop around the controlled element with the desired plant dynamics simulated in the feedback path would implement the desired system rather simply. This type of system is illustrated in Figure 5.

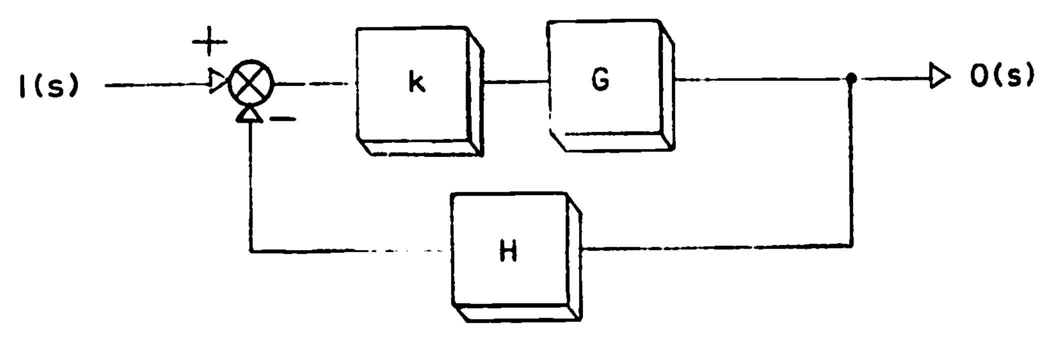


Figure 5. Method of Synthesizing Desired Plant Dynamics

In this figure G represents the dynamics of the controlled element, k is a high gain and 1/H represents the desired plant dynamics. For k very large, the overall transfer function would reduce to 1/H:

$$\frac{O(s)}{I(s)} = \frac{kG}{1 + kGH} \cong \frac{1}{H}$$

Since the Gain-Effective Time Constant condition has illustrated the method of molding only a gain-lead technique, further investigation needs to be made into the proper sequencing of control technique groupings so that positive transfer between these groupings occurs. Once this has been established the adaptive shaping of the plant dynamics necessary to model the specific control technique group is a comparatively simple straight-forward synthesis procedure.

SECTION VI

RECOMMENDATIONS

The results and conclusions of this study lead to the following recommendations:

- o The common elements underlying the Gain-Effective Time Constant product and the correct approach to System Compensation should be used to develop a method for shaping a subject's behavior to produce an optimum describing function.
- o Aiding and quickening as conventionally conceived should not be used as adaptive variables.
- o Candidate adaptive variables should be tested for positive transfer between successive levels after only small amounts of practice.
- o Instructions to subjects should be formulated in such a way as to insure that they do not suggest or imply the use of control techniques which are not appropriate to the task.
- o The differential effects upon transfer from an adaptive trainer to a task of fixed difficulty as a function of performance measurement interval should be investigated.
- o The present work should be extended to include multi-dimensional tasks.

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APPENDIX A

INSTRUCTIONS TO SUBJECTS

You will be performing a task similar to flying an airplane. The green line on the screen representing the horizon will move up and down by different amounts and at different speeds. There is no pattern to the movement, so don't try to find one. The motion of the line is completely random.

You are to try to keep the line centered on the aircraft symbol by moving the STICK on the chair arm back and forth. You will not need to move it from side to side. When the horizon line starts to move up, pull the stick backward momentarily to hold the line down. In the same way, when the line starts down push the stick forward momentarily to hold it up.

The stick controls the speed of movement of the line. The faster the line moves, the further you will want to move the stick. When the line moves away from the center, try to return it as rapidly as possible. You should make only small movements of the stick at first, until you get the feel of it.

You will find it helpful to imagine that you are looking out a window at the horizon and that what the stick is controlling is the airplane. Then, when the airplane drops below the horizon, pull the stick back, and vice-versa.

It will also be helpful to think of "bumping" or "flicking" the stick rather than holding it deflected until something happens. Move the stick, release it, note the result and move again. If you try to wait until the airplane is level before releasing, you will always be behind.

The airplane might appear to respond differently at different times; that is a normal feature of this experiment, don't be surprised.

The line will start moving at the start of a trial and will stop at the end. It will remain where it was at the end of a trial until your score is recorded, and then move to the center. The experimenter will ask whether you are ready before beginning each trial.

Each trial will be 2 min. long. Testing will continue until your performance is stabilized. A 2 min. break will follow every 4 trials. During the break you may relax, rest your eyes, and smoke, if you wish. The height of the screen can be adjusted during a break if you have become uncomfortable. The brightness of the horizon line and aircraft symbol may also be adjusted.

Keep your FACE pressed lightly against the hood during each trial. Also, keep your face against the hood between trials; there will only be a few moments between trials.

There are no "tricks" to this experiment. Your scores indicate only how well you can keep the line centered. Just concentrate on keeping the line centered and do the best you can.

Remember: Keep the airplane level by pulling the stick back momentarily to move it up, pushing forward to move it down, and keep your face against the hood between breaks.

Do you have any questions about what you are to do?

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13. ABSTRACT

Gain-Effective Time Constant product (KT), System Compensation (SC) (a condensation of aiding and quickening) and Forcing Function Amplitude (FF) were compared as adaptive variables in an adaptive training experiment using 104 subjects. Comparison was also made of Automatic and Manual adjustment of the difficulty level determined by the level of the adaptive variables during training. Results showed KT to be slightly superior to FF as an adaptive variable while SC produced poor performance and a high rate of failure. Study of the results suggests that principles underlying KT and a correct form of SC can be used to develop an optimal method of shaping operator behavior. It was concluded that conventional concepts of aiding and quickening cannot be implemented as satisfactory adaptive variables. The results were additionally interpreted to indicate that logic for adjustment of difficulty level should utilize a performance measurement interval longer than 5 seconds.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Adaptive training						
Manual control						
Flight training						